Webinar #6- Physical Science
Part 2: Fluid Dynamics

UNOOSA Hypergravity/Microgravity Webinar
May 26, 2021

Prof. Ryoji Imai

Mурoran Institute of Technology, Japan
Outline

1. How does fluid behave in microgravity?
2. Liquid in container
   → Propellant tank for spacecraft
3. Flow boiling and two-phase flow
   → Thermal management system for space station and spacecraft
4. Marangoni convection
   → Material processing
5. Concluding remarks
1. How does fluid behave in microgravity?

Simple experiment by drop capsule

Acceleration area

Capsule

Liquid in egg shape container

Bear

2m

In the capsule

Oil timer
1. How does fluid behave in microgravity?

What can we find in this experiment?

- Bear floats.  →  Weightlessness
- Liquid in the container becomes round.  →  Surface tension
- Liquid in the container climbs the wall.  →  Surface tension, wetting
- Droplet doesn’t drop, stays.  →  Weightlessness
- Droplet gradually becomes round.  →  Surface tension
1. How does fluid behave in microgravity?

- Droplet doesn’t drop, stays.

How about bubble?

- Bubble doesn’t rise, and stays also.

Boiling bubble

Boiling bubble in microgravity (right)

https://www.nasa.gov/image-feature/pool-boiling-1g-vs-microgravity
1. How does fluid behave in microgravity?

How about natural convection?

Natural convection in 1G
Convection due to buoyancy

Marangoni convection
Convection due to difference of surface tension

2. Liquid in the container

→ Propellant tank for spacecraft
Propellant tank for artificial satellite and spacecraft

Propellant tank for artificial satellite and spacecraft

Surface tension

- Liquid rises higher in narrower gas.
  Liquid tends to gather in narrower space.

- Narrow space is formed on the outlet.
- Propellant will be trapped on the outlet.
3. Flow boiling and two-phase flow

→ Thermal management system for space station and spacecraft
Boiling two phase flow

Two phase thermal management system

Boiling two phase flow
liquid and vapor

Bubbly flow

Slug flow

Annular flow

Thermal characteristics of boiling two phase flow depends on the structure of free surface.
Two-Phase Flow Experiment in ISS

TPF Two Phase Flow

Kyushu Univ., Kobe Univ., Univ. of Hyogo, Tokyo University of Science, The Univ. of Kitakyushu, Muroran Institute of Technology, JAXA, IHI Aerospace, JAMSS, JSF.

Test section
Flange
LED panel
Metallic mirror
High frame-rate camera
Electrode
Heated section
Electrode
Transparent heated tube

Copper heated tube
Unheated test section

33 mm (Interval)
420 mm
19 mm
5 mm
19 mm

70 mm

Electrode
Heated section
Electrode
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power supply to heaters</td>
<td>300 W</td>
</tr>
<tr>
<td>Test fluid</td>
<td>n-perfluorohexane</td>
</tr>
<tr>
<td>Inner diameter of test tubes</td>
<td>$d_i = 4 \text{ mm}$</td>
</tr>
<tr>
<td>Heated length</td>
<td>$l = 50 \text{ mm} \times 2 + 5 \text{ mm} \times 1$ for transparent heated tube $l = 368 \text{ mm}$ for metal heated tube</td>
</tr>
<tr>
<td>Pressure (observation section)</td>
<td>$P = 105 - 125 \text{ kPa}$</td>
</tr>
<tr>
<td>Mass flux</td>
<td>$G = 30-300 \text{ kg/(m}^2\text{s)}$</td>
</tr>
<tr>
<td>Liquid subcooling at inlet of heated test section</td>
<td>$\Delta T_{sub} = 0 - 10 \text{ K}$</td>
</tr>
<tr>
<td>Vapor quality at outlet of heated test section</td>
<td>$x = 0 - 0.71$</td>
</tr>
<tr>
<td>Heat flux</td>
<td>$q = 0 - 28.3 \text{ kW/m}^2$</td>
</tr>
</tbody>
</table>

Size: W 800mm × D 650mm × H 500mm
Mass: 140 kg
Flow pattern map

<table>
<thead>
<tr>
<th></th>
<th>$1G$</th>
<th>$\mu G$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$G$ (kg/(m²·s))</td>
<td>$310$</td>
<td>$330$</td>
</tr>
<tr>
<td>$x$</td>
<td>$0.039$</td>
<td>$0.024$</td>
</tr>
</tbody>
</table>

- **Annular**
- **Slug**
- **Bubble**
- **Churn**

**Legend:**
- $\times$ Bubbly flow
- $\triangle$ Slug flow
- $\bigcirc$ Semi-annular flow
- $\bigstar$ Continuous bubbly flow
- $\bigcirc$ Annular flow
- $\bigtriangleleft$ Continuous Bubble Flow
Boiling behaviors in the glass heating tube (G=100 kg/(m²s))

Higher heat transfer coefficient

1G (vertically upward)

\[ q = 14.5 \text{ W/m}^2 \]

\[ q = 18.6 \text{ W/m}^2 \]

\[ q = 26.9 \text{ W/m}^2 \]

\[ q = 14.1 \text{ W/m}^2 \]

\[ q = 20.0 \text{ W/m}^2 \]

\[ q = 28.3 \text{ W/m}^2 \]
4. Marangoni convection

→ Material processing
Production of semiconductor materials

Marangoni convection during the production of crystals such as for semiconductor and oxide material negatively affect the quality of the crystals.


Striations in the crystal due to oscillatory Marangoni convection

Floating zone method

Grown crystal of GaSb both in microgravity and on earth
Flow Transition

Flow Transition from Steady to Oscillatory, Turbulence

T. Yano et al., Microgravity Science and Technology (2018)
The history of microgravity experiments on Marangoni convection in liquid bridges.

\[ Ma = \left| \frac{\sigma_T}{\mu} \frac{\Delta TH}{\alpha} \right| \]

Prandtl number \( Pr = \frac{\nu}{\alpha} \)

Aspect ratio \( AR = \frac{H}{D} \)

Volume ratio \( VR = \frac{V}{V_0} \)

Biot number \( Bi = \frac{hH}{\lambda_l} \)
Marangoni convection Experiment in ISS MEIS  Marangoni Experiment In Space

Tokyo University of Science, JAXA, Yokohama National University, JAMSS, JSF, IHI Aerospace

Liquid Bridge size
Diameter: 10, 30, 50 mm, Height: up to 62.5 mm

Experiment Sample
Silicone Oil (viscosity; 5, 10, 20 cSt)
Pr = 67, 112, 207

T. Yano et al., Microgravity Science and Technology (2018)
Fig. 8 Particle trajectories obtained by 3-D PTV for $A = 1.25$: (a) MEIS-2, (b) DS-3, (c) MEIS-3, and (d) MEIS-4. The experimental conditions are listed in Table 4.
Estimated transition diagram

Critical Marangoni number $Ma_c$

Steady

Oscillatory

Turbulent

Marangoni number $Ma = \frac{|\sigma_T| \Delta TH}{\mu \alpha}$

Prandtl number $Pr = \frac{\nu}{\alpha}$

smaller $\Delta T$  
greater $\Delta T$

Higher temperature plane  
Lower temperature plane

Matsumoto et al., 2008  
Schwabe et al. 1990  
Kawaji and Yoda et al. 2001  
Nishino et al., 2011  
Yoda and Matsumoto et al., 2011

$Pr = \frac{\nu}{\alpha}$
Concluding Remarks

As the fluid dynamics under microgravity, following three examples were introduced.

✓ Liquid in container
✓ Flow boiling and two-phase flow, ISS experiments
✓ Marangoni convection, ISS experiments

There are following subjects which I could not present today
Complex fluids, Interfacial Phenomena, Capillary Flow Phenomena, Colloids and Suspensions, Liquid Crystals (Structure and Dynamic Studies), Foams, Granular Materials, Magnetorheological Fluids, Polymer Fluids,
Thermal and fluid dynamics related to propulsion system in future spacecraft